# Load Estimation of Intelligent Tires Equipped with Acceleration Sensors

Dasol Jeong, Jonghyup Lee, and Seibum Choi
*Department of Mechanical Engineering*
*KAIST, Korea Advanced Institute of Science and Technology*
Daejeon, Korea
oieiaa@kaist.ac.kr, sonic_92@kaist.ac.kr, sbchoi@kaist.ac.kr

Mintae Kim
*R&D Center*
*HANKOOK TIRE CO. LTD*
Daejeon, Korea
mtkim@hankooktire.com

***Abstract*—Vehicle load and tire load play an important role in estimating vehicle parameters and vehicle control. In previous studies, the tire load was estimated based on vehicle dynamics. However, the load estimation algorithm based on vehicle dynamics is highly dependent on the vehicle parameters and has a long estimation time and low accuracy. This paper proposes a new load estimation algorithm using an intelligent tire sensor. The proposed algorithm is analyzed through a flexible ring tire model, which is a physical tire model, and is constructed based on the relationship between load-contact angle-pressure. The performance of the load estimation algorithm is verified by indoor tests using Flat trac. As a result, fast estimation times and high estimation accuracy are confirmed under various conditions.**

***Keywords— intelligent tire, tire load estimation, flexible ring tire model***

## I. Introduction

Tires, which are the only part to contact the road surface in the vehicle system, contain a lot of information. In addition, the forces and moments between the tire and the road surface were the most important factors in the acceleration, deceleration and steering of the vehicle. Therefore, estimating various information of tire was important research in vehicle control. Especially, the tire load is very important for vehicle control and various vehicle parameter estimation. That is, the total load of the vehicle and the load applied to each wheel are directly related to the performance and accuracy of the model based control, the powertrain system, the ABS system, and the road slope estimation.

In previous studies, the estimation of the vehicle load and tire load was studied mostly based on vehicle dynamics [1], [2]. However, the load estimation algorithms based on vehicle dynamics have some limitations. First, since it depends on the model parameters of the vehicle, the error of the vehicle parameters was directly related to the error of the estimation algorithm. Second, the estimated time was very long because the load was estimated only in a situation that satisfied certain conditions. Also, even if the total load of the vehicle was estimated based on vehicle dynamics, the estimation error was greatly increased when the load was distributed to each wheel. Therefore, this paper introduces the load estimation algorithm through intelligent tire sensors rather than based on vehicle dynamics.

Intelligent tire was a new concept tires with additional sensors inside the tires. Intelligent tires were designed to estimate tire information that was very important, but hard to find [3]. However, there are many difficulties using intelligent tires. First, additional costs are incurred when using the new sensor. In addition, it has difficulties in installing, wireless communications and battery. Despite the difficulties, many researches have been done because of the merits of getting new information on the car and tire.

In recent years, intelligent tire studies have been actively conducted to estimate vehicle states such as sideslip angle [4], [5], tire force [6], [7], and road condition [8], [9]. However, most of the intelligent tire researches have been based on data-based phenomenon observations. These research methods have disadvantages in that they can't ensure the generality and robustness of the estimation algorithm. Therefore, in this study, a flexible ring tire model [10], [11], a physical model of tires, was used in analyzing intelligent tire sensor signals.

The main goal of this paper is the proposal of a new load estimation algorithm through intelligent tires. The proposed algorithm has faster estimation time and higher accuracy than load estimation based on vehicle dynamics. In addition, it has advantages in generality and robustness compared to other intelligent tie researches because it was analyzed through the flexible ring tire model. The estimated tire load will be used as important information for vehicle control.

The rest of this paper is organized as follow. Section 2 describes the test environment. In section 3, the tire load is analyzed through flexible ring tire model. Section 4 proposes a new load estimation algorithm, and section 5 presents load estimation results in indoor test.

978-1-5386-7713-1/19/$31.00 ©2019 IEEE

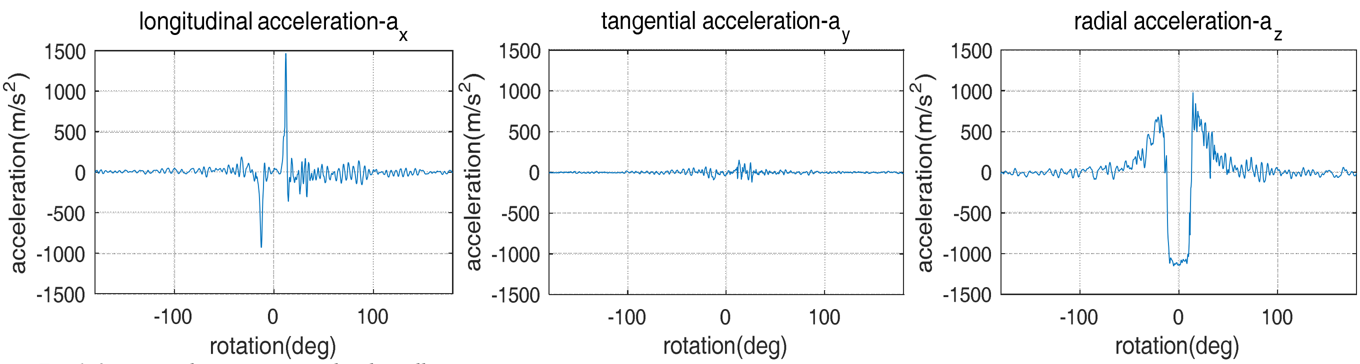


*Fig. 1. 3-axis acceleration measured with intelligent tire sensor.*

## II. TEST ENVIRONMENT

There were two types of intelligent tire sensors: accelerometer, strain gage. Accelerometers are more sensitive to noise than strain gages and require advanced signal processing techniques. However, accelerometers had the advantage of compact size, high-energy efficiency and low cost [3]. Therefore, in this study, an accelerometer was selected and attached to the tire inner linear considering durability.

A three-axis accelerometer was used as a sensor of the intelligent tire. The measurable range of the sensor is -2000 g ~ +2000 g and the sampling rate is 9600 Hz. The accelerometer was attached to the inner liner (inner surface) of the tire. In addition, the sensor was attached to the exact center of the lateral direction. Then, the direction of the x-axis acceleration was set to the longitudinal direction, which was the rotation direction of the tire, the y-axis acceleration was set to the lateral axis, and the z-axis was set to radial direction. After setting the direction of the sensor, data was collected as shown in the Fig. 1.

For the test machine, the experiment was carried out using the Flat trac as shown in the Fig. 2. Flat trac has the advantage of being able to experiment easily by changing various conditions. The experiments were carried out for 2 seconds at constant speed with the load applied to the tires. The experiments were repeated by changing experimental conditions. The experiment variables were load, pressure, wear and speed as shown in Table 1. In conclusion, 3-axes sensor data (longitudinal, lateral, radial) were collected for 72 conditions..


*Fig. 2. The Flat trac used in the indoor test.*

*TABLE I. Experimental conditions.*

| Condition | Level |
|---|---|
| **Load** | Light, Normal, Heavy |
| **Pressure** | Low, Normal, High |
| **Velocity** | Slow, Normal |
| **Wear** | New, Intermediate, Recommended minimum, Legal limit |

## III. FLEXIBLE RING TIRE MODEL

In the case of tire modeling, much research has been done to find out the contact characteristics of the tires. Among them, the flexible ring tire model was the most similar to the real tire, and good for representation the tire characteristics. In the flexible ring tire model, in-tire radial deformation (w) and in-tire longitudinal deformation (v) were expressed. These are the deformations of the sensor attachment position in the intelligent tire, so that the physical meaning of the sensor data can be analyzed through tire model. In other words, the accelerometer of the intelligent tire measures $\ddot{v}$ and $\ddot{w}$ on the x-axis and z-axis. In addition, flexible ring tire model has the advantage of being able to analyze tire deformation by changing the load, pressure, speed and tread depth. In this paper, the relationship between tire load and other tire parameters was analyzed by using the flexible ring tire model.

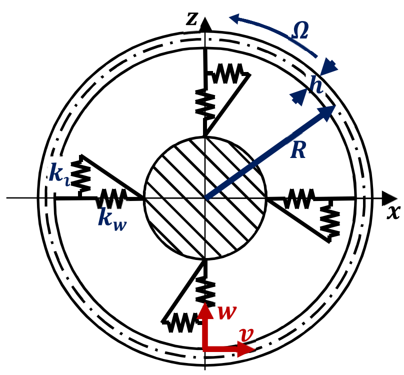


*Fig. 3. Flexible ring tire model*

## A. Gorvening Equation of Flexible Ring Tire Model

The governing equations of the Tire motion were made by combining Hamiltonian equations of various energy (strain energy, elastic energy, kinetic energy, virtual work of external force) between the tire and the road surface. Equation (1), (2) are the governing equation of the tire model analyzed in the previous study [10].

$$\frac{EI}{R^4}\left(\frac{\partial^4 w}{\partial\theta^4}-\frac{\partial^3 v}{\partial\theta^3}\right)+\frac{EA}{R^2}\left(w+\frac{\partial v}{\partial\theta}\right)+\frac{\sigma_\theta^0 A}{R^2}\left(\frac{\partial v}{\partial\theta}-\frac{\partial^2 w}{\partial\theta^2}\right)$$
$$+k_w(w-x^*\cos\theta\ \ -z^*\sin\ \theta)+\rho A(\ddot{w}-2\Omega\dot{v}-\Omega^2 w)$$
$$+c_w(\dot{w}+\Omega w')-\frac{p_0 b}{R}\left(\frac{\partial v}{\partial\theta}+w\right)=q_w \tag{1}$$

$$\frac{EI}{R^4}\left(\frac{\partial^3 w}{\partial\theta^3}-\frac{\partial^2 v}{\partial\theta^2}\right)+\frac{EA}{R^2}\left(\frac{\partial w}{\partial\theta}+\frac{\partial^2 v}{\partial\theta^2}\right)+\frac{\sigma_\theta^0 A}{R^2}\left(v-\frac{\partial w}{\partial\theta}\right)$$
$$+k_v(v+x^*\sin\theta\ \ -z^*\cos\theta\ \ -R\theta_r)+\rho A(\ddot{v}+2\Omega\dot{w}-\Omega^2 v)$$
$$+c_v(\dot{v}+\Omega v')+\frac{p_0 b}{R}\left(\frac{\partial w}{\partial\theta}-v\right)=q_v \tag{2}$$

The above governing equation can be expressed as a mass-spring-damper system through in-extensibility assumption [11].

$$\frac{p_0 b}{R}w'\ -(c_w+c_v)\Omega w'+\left(\frac{p_0 b}{R}-k_w-k_v\right)w=q_v'-q_w \tag{3}$$

In addition, it is possible to simplify the equation through the assumption that the tire deformation is symmetric about the center($\mathrm{c_w}=c_v=0$) and the longitudinal force distribution is zero($\mathrm{q_v}=0$).

- Non-contact region: $\frac{\mathrm{p_0} b}{R}w'\ +\left(\frac{p_0 b}{R}-k_w-k_v\right)w=0$ (4)
- Contact region: $\frac{\mathrm{p_0} b}{R}w'\ +\left(\frac{p_0 b}{R}-k_w-k_v\right)w=-q_w$ (5)

## B. Geometrical Assumption

Additional geometrical assumptions have been considered to analyze tire loads through the flexible ring tire model. This assumption is that the deformation is flat on the contact area and the road surface is frictionless. That is, the tire was deformed as shown in the Fig. 4 and $\mathrm{w_c}$(radial deformation in the contact region) is defined as follows [11].

$$\mathrm{w_c}=R-\frac{R-\delta}{\cos\theta} \tag{6}$$

Where $R$ is radius of tire, $w_c$ is radial deformation within the contact region, $\delta$ is maximum radial deformation

Also $\delta\approx\mathrm{R}-\mathrm{R}\cos(\theta_\mathrm{r})$ and finally $\mathrm{w_c}$ was expressed as follows.

$$\mathrm{w_c}=R\left(1-\frac{\cos\theta_\mathrm{r}}{\cos\theta}\right) \tag{7}$$

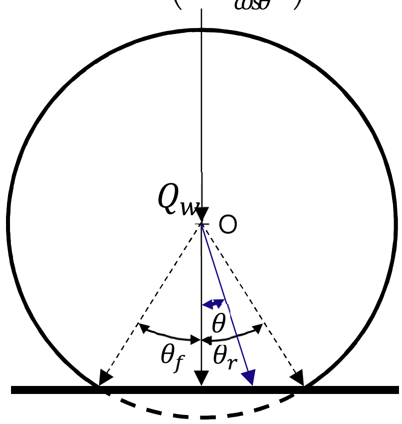


*Fig. 4. Tire deformations in the contact region*

## C. Expression of the Tire Load

In this section, the expression of the load applied to the tire is derived through the flexible ring tire model. In the flexible ring tire model, the load applied to the tire is expressed as follows. Also, since tire deformation was assumed to be symmetric, so $\theta_f=\theta_r$

$$\mathrm{Q_W}=R\int_{\theta_\mathrm{f}}^{\theta_\mathrm{r}} q_w\cos\theta\, d\theta \tag{8}$$

Where $Q_w$ is tire load, $q_w$ is radial force distribution, $\theta_f$ is forward edge contact angle, $\theta_r$ is rear edge contact angle

Finally, the tire load can be expressed by (5), (7) and (8)

$$Q_w=2Rp_0 b\sin\theta_r+2R^2(k_w+k_v)(\sin\theta_r-\theta_r\cos\theta_r) \tag{9}$$

Equation (9) means that the tire is composed of several parameters and elements, but the load applied to the tire is determined only by the pressure($p_0$), sidewall stiffness($k_w+k_v$), contact angle($\theta_r$). In this case, the sidewall stiffness does not change because it is a characteristic of the tire. In conclusion, the load applied to the tire can be expressed as a function of pressure and the contact angle as shown below.

$$Q_w=f\left(p_0,\ \text{Contact angle}(\theta_r)\right) \tag{10}$$

Hence, it has been verified that the tire load can be estimated based on the tire pressure and contact angle.

## IV. Load Estimation Algorithm

### A. Estimation of Contact Angle

The contact angle can be easily estimated from the acceleration sensor data of the intelligent tire. The longitudinal acceleration measured by the acceleration sensor is shown in Fig. 5. Physically, at the forward edge and rear edge, the tread is released in the longitudinal direction and the maximum force is applied. That is, the contact angle is estimated as the angle between the peak points of the longitudinal acceleration as shown in Fig. 5.

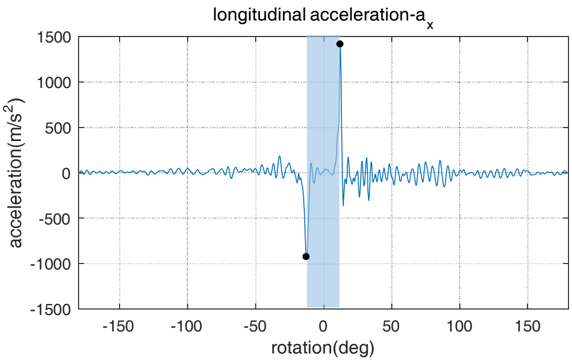


*Fig. 5. Longitudinal acceleration: Blue box means contact area.*

### B. Load Estimation Algorithm

In section III, it had been proven through the flexible ring tire model that the tire load was dominantly determined by contact angle and pressure. In addition, the relationship of load-contact angle-pressure was verified under various conditions before constructing the load estimation algorithm.

Fig. 6 shows the relationship of contact angle - load - pressure under various conditions. Thick lines of different colors represent different pressures. Each bold line contains a load-contact angle-pressure graph in eight different conditions (two levels of velocity, four levels of wear). That is, the thickness of each thick line indicates the influence of velocity and wear. In conclusion, it is verified that the load is dominant in pressure contact angle, and not dominant in other conditions.

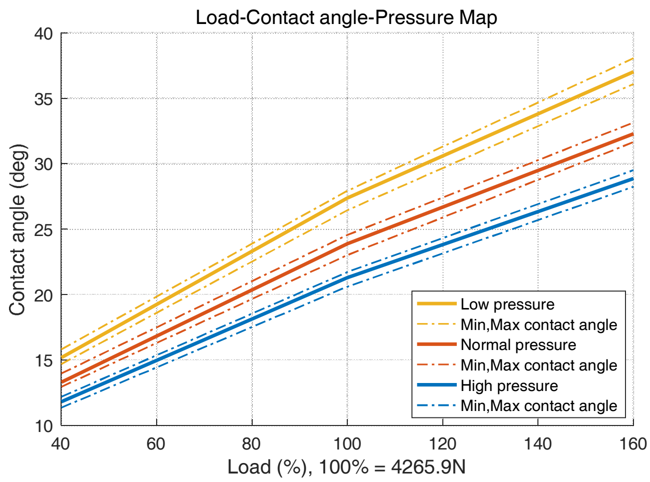


*Fig. 6. Relationship between load-contact angle-pressure.*

Finally, the load estimation algorithm is constructed based on the load-contact angle-pressure map as shown in the Fig. 7. That is, when the measured pressure and the estimated contact angle are input to the three-dimensional map, the tire load is output.

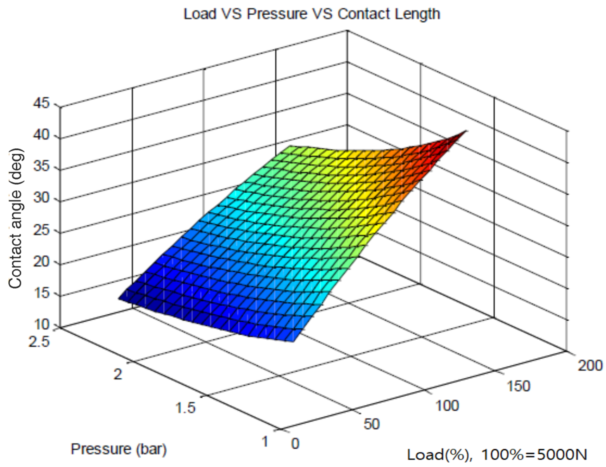


*Fig. 7. Three-dimensional map of load-contact angle-pressure.*

## V. Load Estimation Results

The performance of the load estimation algorithm using the intelligent tire sensor is verified through the indoor test using the Flat trac. The indoor tests were performed with three loads(light, normal, heavy) and two velocities(slow, normal) for each pressure level for 2 seconds.

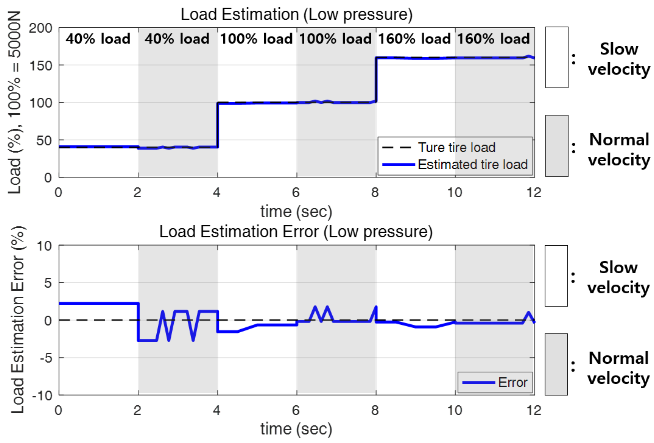


*Fig. 8. Load estimation results at low pressure. (a) Estimated tire load, white: slow velocity gray: normal velocity, (b) error of load estimation.*

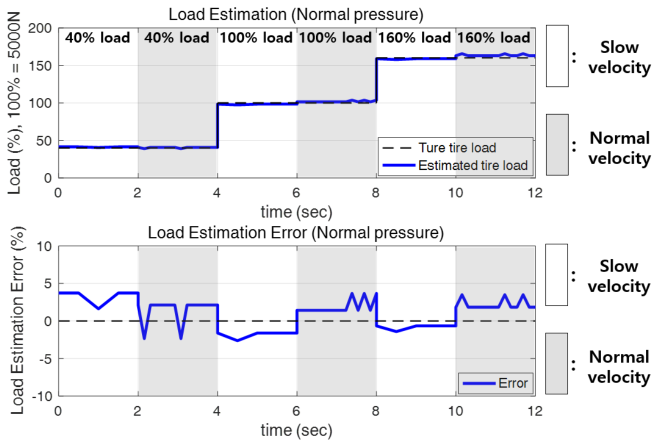


*Fig. 9. Load estimation results at normal pressure. (a) Estimated tire load, white: slow velocity gray: normal velocity, (b) error of load estimation.*

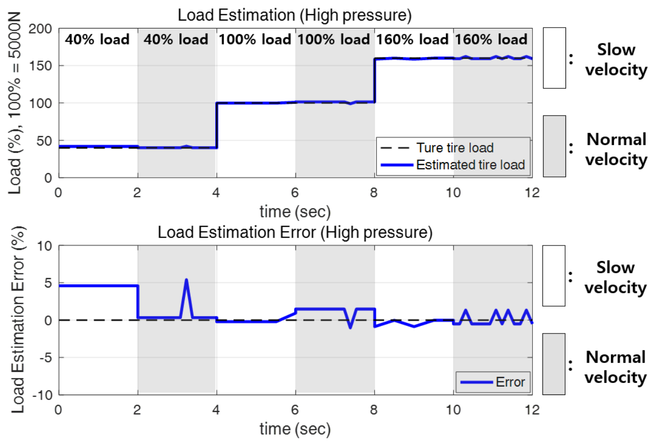


*Fig. 10. Load estimation results at high pressure. (a) Estimated tire load, white: slow velocity gray: normal velocity, (b) error of load estimation.*

The results of the load estimation are shown in the Fig. 8 - Fig. 10. Experimental results show that the tire load can be estimated even if the load, pressure, and speed change. Also, the error is less than 5% under all conditions and shows good performance. This confirms that the load- contact angle-pressure map shown in Fig. 7 is implemented correctly. Furthermore, it has been proved that the load estimation algorithm is robust for various conditions such as velocity and wear.

In conclusion, the proposed load-estimation algorithm is physically analyzed through flexible ring tire model and its performance is verified experimentally. In addition, the estimated load information through the proposed load estimation algorithm can be used for overarching notification, and it is expected that it can be used for vehicle control system and autonomous driving.

## VI. Conclusion

In this paper, load estimation algorithm using intelligent tire sensors is proposed. The load-estimation algorithm is based on the relationship between load, contact angle and pressure, which is analyzed through a flexible ring tire model. Then, a three-dimensional map of the load-pressure-contact angle is constructed, and the load is estimated using the estimated contact angle from the intelligent tire and the measured pressure as inputs. Finally, the load estimation algorithm is experimentally verified through an indoor test using a Flat trac. As a results, fast estimation times and high estimation accuracy are confirmed.

## Acknowledgment

This research was partly supported by the Industrial Strategic Technology Development Program funded by the HANKOOK TIRE CO.LTD.; the BK21+ program through the NRF funded by the Ministry of Education of Korea; and the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIP) (No. 2017R1A2B4004116.

## References

[1] Vahidi, Ardalan, Anna Stefanopoulou, and Huei Peng, Recursive least squares with forgetting for online estimation of vehicle mass and road grade: theory and experiments, Vehicle System Dynamics, VOL.43, No.1, pp.31-55, January, 2005.

[2] Fathy, Hosam K., Dongsoo Kang, and Jeffrey L. Stein, Online vehicle mass estimation using recursive least squares and supervisory data extraction, American Control Conference, June, 2008.

[3] Lee, Hojong, and Saied Taheri, Intelligent Tires? A Review of Tire Characterization Literature, IEEE Intelligent Transportation Systems Magazine VOL.9, No.2, pp.114-135, April, 2017

[4] Erdogan, Gurkan, et al, Tire sensors for the measurement of slip angle and friction coefficient and their use in stability control systems, SAE International Journal of Passenger Cars-Mechanical Systems, VOL.4, No1, pp.44-58, December, 2011

[5] G. Erdogan, L. Alexander, and R. Rajamani, A novel wireless piezoelectric tire sensor for the estimation of slip angle, Measurement Science and Technology, VOL.21, September, 2009.

[6] Savaresi, Sergio M., et al, New regressors for the direct identification of tire deformation in road vehicles via" in-tire" accelerometers, IEEE Transactions on Control Systems Technology VOL.16, No.4, pp.769-780, July, 2008

[7] Braghin, Francesco, et al, Measurement of contact forces and patch features by means of accelerometers fixed inside the tire to improve future car active control, Vehicle System Dynamics, VOL.44, pp.3-13, 2006

[8] Singh, Kanwar Bharat, Developing Enabling Technologies for Intelligent Tires, 23rd Aachen Colloquium Automobile and Engine Technology, 2014.

[9] Niskanen, Arto, and Ari J. Tuononen, Three three-axis IEPE accelerometers on the inner liner of a tire for finding the tire-road friction potential indicators, Sensors, VOL15, No.8, pp.19251-19263, August, 2015

[10] Gong, S, A Study of In-Plane Dynamics of Tires, TU Delft, Delft University of Technology, 1993.

[11] Yu, Zeng-Xin, et al, A simple analysis method for contact deformation of rolling tire, Vehicle System Dynamics, VOL.36, No.6, pp.435-443, 2001.